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(71) Applicant: AMOCO CORPORATION [US/US]; Mail Code 1907A, Patents and Licensing Department, 200 East Randolph Drive, P.O. Box 87703, Chicago, IL 60680-0703 (US).

(72) Inventor: TIDWELL, Steve, C. ; 20829 59th Ave., S.E., Woodinville, WA 98072 (US).

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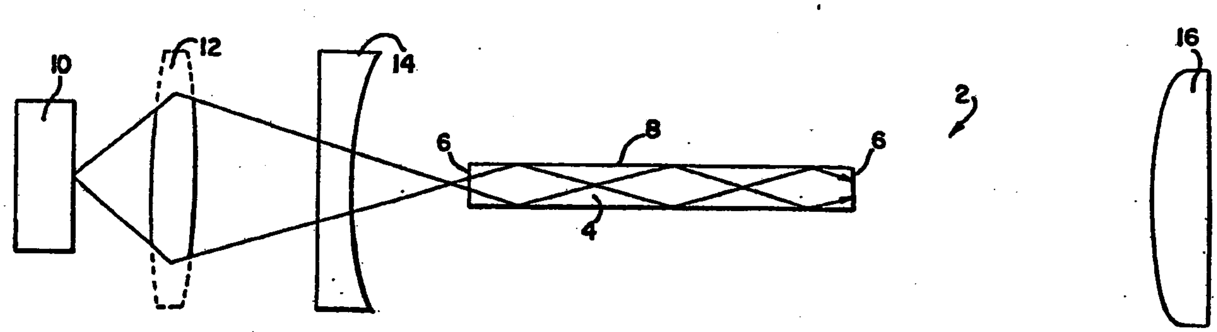
(54) Title: UNIFORM END PUMPING FOR LASER AMPLIFIERS AND SOURCES



(57) Abstract

A method and apparatus for uniformly end-pumping a laser source or amplifier by reflecting pump radiation from the side surface of the lasing medium as it travels through the lasing medium.

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Uniform End Pumping for Laser Amplifiers and Sources

Field of the Invention

The invention relates to configurations for end pumping laser amplifiers and sources, and more particularly to methods and apparatus for uniformly end pumping laser amplifiers and sources.

Background of the Invention

The lasing medium that used in most solid state laser amplifiers and sources is generally rod-shaped, and is optically pumped by at least one pumping source that is generally adjacent to the outer circumferential surface of the lasing medium or at least one of the two opposed ends. The first method is called side-pumping and the second is called end-pumping.

Side pumped systems are the most common because of the ease of coupling the pumping source to the lasing medium. However, side-pumping does not efficiently couple the energy from the pumping source to the lasing medium for at least two reasons. First, the lasing medium must comprise a relatively thin rod, on the order of three to four millimeters, to achieve a gain level that is needed for efficient beam extraction. With typical laser diode pumping sources, only about seventy percent of the incident pump power is absorbed through a lasing medium thickness of three millimeters.

Also, since the absorption of the pumping source energy is exponential, most of the energy is distributed near the outer surface of the lasing medium where it cannot be extracted by a TEM_{00} mode. The absorption efficiency and uniformity can change significantly with variations in the wavelength of the pump radiation. Various arrangements have been proposed for improving the performance of side-pumped lasers, but they all add complexity without achieving optimal efficiency and uniformity of the distributed pumping energy.

End pumped lasers offer much higher absorption of pump energy and lower sensitivity to variations in the wavelength of the pump radiation since the radiation is absorbed along the long axis of the rod. In prior art, the pump light is focused into the center of the rod to provide the best overlap between the laser mode and the pump radiation. Changes in the wavelength of the pump radiation can result in variations in the output power because the mode/pump overlap can be affected. When the average absorbed pump power is above approximately ten watts, thermal effects can dominate laser performance. For instance, Nd:YLF can fracture and Nd:YAG exhibits strong thermal focus, aberrations and stress-induced birefringence. Thermal difficulties are encountered at lower powers in end-pumped lasers due to the high degree of nonuniformity in the pump power distribution in the lasing medium.

Summary of the Invention

According to the invention, the laser system is end-pumped in a way that the pump source photons are captured in the rod so they reflect back and forth down the lasing medium until absorbed. Reflection of the pump source photons is conveniently achieved by directing the pump radiation into the medium so that the side surface of the lasing medium reflects the pump photons by substantially total internal reflection or with the application of suitable lasing medium surface coatings,treatments, or the combination thereof. This method of pumping combines efficient absorption of pump energy with low sensitivity to variations in wavelength of pump radiation. The high absorption efficiency combined with high absorption uniformity allows high gains to be secured with a lasing medium that comprises a small diameter rod. the residual heat in the laser rod can be distributed over the rod length so that the thermal scaling behavior of the system is better than conventional end-pumped lasers. The pump energy can be extracted efficiently in a high beam quality mode using a graded-reflectivity mirror unstable resonator. The high gain also allows for efficient extraction in amplifier applications.

In the preferred embodiment, the invention comprises a method of end-pumping a laser system having a lasing medium with two generally opposed end surfaces and a generally circumferential side surface, comprising the steps of: transmitting pumping radiation toward at least one of said end surfaces of said lasing medium; and directing said transmitted pumping radiation to reflect from said side surface of said lasing medium as is passes through said lasing medium.

In the preferred embodiment, the invention comprises an apparatus for end-pumping a laser system having a lasing medium with two generally opposed end surfaces and a generally circumferential side surface, comprising: means for transmitting pumping radiation toward at least one of said end surfaces of said lasing medium; and means for directing said transmitted pumping radiation to reflect from said side surface of said lasing medium as is passes through said lasing medium.

Description of the Drawings

Figure 1 is a schematic diagram of a first embodiment of the invention.

Figure 2 is a schematic diagram of a second embodiment of the invention.

Description of the Invention

Referring to the drawings, wherein reference characters designate like or corresponding parts throughout the views, Figure 1 is a schematic diagram of a first embodiment of the invention. A laser system 2 includes a solid-state lasing medium 4. Although the laser system 2 is represented as a laser source in Figure 1, it may alternatively comprise a laser amplifier. The lasing medium 4 has two generally opposed end surfaces 6 and a generally circumferential side surface 8.

At least one means for transmitting pump radiation, typically at least one source of pump radiation 10, transmits pump energy

toward at least one of the ends 6 of the lasing medium 4. In Figure 1, a single source of pump radiation 10, typically a laser diode source, is shown. The path of at least a portion of the pump radiation from the source of pump radiation 10 is controlled by at least one means for directing the pump radiation 12, directs the pump radiation into the lasing medium 4 through at least one of the ends 6. In Figure 1, a single means for directing the pump radiation 12, typically a lens system, is shown. Alternatively, the means for directing the pump radiation 12 may comprise another suitable optical system, such as a prism system.

For the laser system 2 shown in Figure 1, a single means for directing the pump radiation 12 is sufficient for directing the pump radiation transmitted from the single source of pump radiation 10 into the lasing medium 4 through one of the ends 6. According to one aspect of the invention, the means for directing the pump radiation 12 directs the path of the transmitted pump radiation to intersect the side surface 8 of the lasing medium 4 from within the lasing medium 4 at an angle of incidence that is less than or equal to a predetermined angle.

This angle of incidence allows the side surface 8 to reflect the directed pump radiation that strikes it by substantially total internal reflection. Preferably, this angle of incidence is also small enough to allow multiple reflections of the directed pump radiation as it passes through the lasing medium 4. In this way, the reflected pumping radiation is relatively uniformly distributed within the lasing medium 4 from one of the ends 6 to the other end 6.

Alternatively, a reflective coating may be applied to the side surface 8 of the lasing medium 4 to support reflection of the directed pumping radiation through the lasing medium 4. In this case, the angle of incidence may be greater than would allow reflection by total internal reflection. This allows the directed pump radiation to be reflected by the coated side surface 8 a greater number of times than by total internal reflection as it passes through the lasing medium 4.

The reflective coating that is applied to the side surface 8 may be specular or diffusive. A diffusive reflective coating will provide a greater number of path lengths of the pumping radiation that is reflected back and forth within the lasing medium 4, thereby providing even more uniformity of the pumping radiation distribution in the lasing medium 4.

According to another aspect of the invention, the side surface 8 of the lasing medium 4 may be treated, such as by etching or grinding, to provide a rough enough of a surface to reflect most of the directed pumping radiation that strikes the side surface 8 from within the lasing medium 4. Alternatively, the treated side surface 8 may then have a reflective coating applied to it, to reflect even more of the directed pumping radiation than with the surface treatment alone.

The multiple reflections and long absorption path lengths of the pump radiation that is directed through the lasing medium 4 makes it ideal for applications wherein the source of pumping radiation 10 is a laser diode source, since laser diode sources typically have wide variations in bandwidth and center wavelength.

The laser system 2 shown in Figure 1 is represented as a laser source, wherein a dichroic element 14, typically a mirror, is positioned between the means for directing 12 and one of the ends 6 of the lasing medium 4. The dichroic element 14 is highly transmissive for the wavelengths of the pumping radiation and highly reflective for the lasing wavelengths. The laser system 2 also has an output coupler 16 that has sufficient reflectivity at the lasing wavelength to sustain oscillation. The output coupler 16 preferably comprises a graded-reflectivity mirror. Of course, where the laser system 2 comprises a laser amplifier, the dichroic element 14 and the output coupler 16 are replaced by an input wavelength division multiplexer (WDM) and output WDM, respectively.

Figure 2 is a schematic diagram of a second embodiment of the invention. A laser system 18 includes the solid-state lasing

medium 4 described for the first embodiment in connection with Figure 1. Although the laser system 2 is represented as a laser source in Figure 2, it may alternatively comprise a laser amplifier. The lasing medium 4 has the two generally opposed end surfaces 6 and the generally circumferential side surface 8.

The laser system 18 also has a plurality of means for transmitting pump radiation, typically a plurality of the sources of pump radiation 10, to transmit pump energy toward at least one of the ends 6 of the lasing medium 4. In Figure 1, four of the sources of pump radiation 10, typically laser diode sources, are shown. The path of at least a portion of the pump radiation from each source of pump radiation 10 is controlled by at least one of the means for directing the pump radiation 12, to direct the pump radiation into the lasing medium 4 through at least one of the ends 6. In Figure 1, four of the means for directing the pump radiation 12, typically a lens system, are shown. Alternatively, the means for directing the pump radiation 12 may comprise another suitable optical system, such as a prism system.

Each of the means for directing the pump radiation 12 directs pump radiation that is transmitted from a corresponding one of the sources of pump radiation 10. In Figure 2, the pump radiation from two of the sources of pump radiation 10 are directed into the lasing medium 4 through one of the ends 6 and the other sources of pump radiation 10 are directed into the lasing medium 4 through the other one of the ends 6.

Just as for the laser system 2 described in connection with Figure 1, each of the means for directing the pump radiation 12 is sufficient for directing the pump radiation transmitted from a corresponding one of the sources of pump radiation 10 into the lasing medium 4 through one of the ends 6. According to one aspect of the invention, each of the means for directing the pump radiation 12 directs the path of the transmitted pump radiation from the corresponding one of the sources of pump radiation 10 to intersect the side surface 8 of the lasing medium 4 from within the lasing

medium 4 at an angle of incidence that is less than or equal to a predetermined angle.

This angle of incidence allows the side surface 8 to reflect the directed pump radiation that strikes it by substantially total internal reflection. Preferably, this angle of incidence is also small enough to allow multiple reflections of the directed pump radiation as it passes through the lasing medium 4. In this way, the reflected pumping radiation is relatively uniformly distributed within the lasing medium 4 from one of the ends 6 to the other end 6.

Alternatively, a reflective coating may be applied to the side surface 8 of the lasing medium 4 to support reflection of the directed pumping radiation through the lasing medium 4. In this case, the angle of incidence may be greater than would allow reflection by total internal reflection. This allows the directed pump radiation to be reflected by the coated side surface 8 a greater number of times than by total internal reflection as it passes through the lasing medium 4.

The reflective coating that is applied to the side surface 8 may be specular or diffusive. A diffusive reflective coating will provide a greater number of path lengths of the pumping radiation that is reflected back and forth within the lasing medium 4, thereby providing even more uniformity of the pumping radiation distribution in the lasing medium 4.

According to another aspect of the invention, the side surface 8 of the lasing medium 4 may be treated, such as by etching or grinding, to provide a rough enough of a surface to reflect most of the directed pumping radiation that strikes the side surface 8 from within the lasing medium 4. Alternatively, the treated side surface 8 may then have a reflective coating applied to it, to reflect even more of the directed pumping radiation than with the surface treatment alone.

The multiple reflections and long absorption path lengths of the pump radiation that is directed through the lasing medium 4

makes it ideal for applications wherein the sources of pumping radiation 10 are laser diode sources, since laser diode sources typically have wide variations in bandwidth and center wavelength.

The laser system 18 shown in Figure 2 is represented as a laser source, wherein a highly reflective element 20, typically a mirror, is positioned between two of the means for directing 12. The highly reflective element 20 is highly reflective for the lasing wavelengths. The laser system 18 also has the output coupler 16 that has sufficient reflectivity at the lasing wavelength to sustain oscillation. Again, the output coupler 16 preferably comprises a graded-reflectivity mirror. Of course, where the laser system 18 comprises a laser amplifier, the highly reflective element 20 and the output coupler 16 are replaced by an input wavelength division multiplexer (WDM) and output WDM, respectively.

Thus, there has been described herein methods and apparatus for uniformly end-pumping a laser source or amplifier by reflecting pump radiation from the side surface of the lasing medium as it travels through the lasing medium. It will be understood that various changes in the details, materials, steps and arrangements of parts that have been described and illustrated above in order to explain the nature of the invention may be made by those of ordinary skill in the art within the principle and scope of the present invention as expressed in the appended claims.

What is claimed is:

1. A method of end-pumping a laser system having a lasing medium with two generally opposed end surfaces and a generally circumferential side surface, comprising the steps of:

transmitting pumping radiation toward at least one of said end surfaces of said lasing medium; and

directing said transmitted pumping radiation to reflect from said side surface of said lasing medium as is passes through said lasing medium.

2. The method set forth in claim 1, wherein said step of directing comprises directing said transmitted pumping radiation to reflect from said side surface of said lasing medium by substantially total internal reflection.

3. The method set forth in claim 1, further comprising the step of applying a reflective coating to said side surface of said lasing medium and wherein said step of directing comprises directing said transmitted pumping radiation to reflect from said reflective coating.

4. The method set forth in claim 3, wherein said step of applying a reflective coating to said side surface of said lasing medium comprises the application of a specular reflective coating to said side surface of said lasing medium.

5. The method set forth in claim 3, wherein said step of applying a reflective coating to said side surface of said lasing medium comprises the application of a diffusive reflective coating to said side surface of said lasing medium.

6. The method set forth in claim 1, further comprising the steps of:

treating said side surface of said lasing medium to be diffusive;

applying a reflective coating to said treated side surface of said lasing medium; and

wherein said step of directing comprises directing said transmitted pumping radiation to diffusively reflect from said reflective coating.

7. The method set forth in claim 6, wherein said step of treating comprises the step of etching said side surface.

8. The method set forth in claim 6, wherein said step of treating comprises the step of grinding said side surface.

9. The method set forth in claim 1, wherein said step of transmitting said pumping radiation toward at least one of said end surfaces of said lasing medium comprises transmitting a single source of said pumping radiation toward a single one of said end surfaces of said lasing medium.

10. The method set forth in claim 1, wherein said step of transmitting said pumping radiation toward at least one of said end surfaces of said lasing medium comprises transmitting a plurality of sources of said pumping radiation toward a single one of said end surfaces of said lasing medium.

11. The method set forth in claim 1, wherein said step of transmitting said pumping radiation toward at least one of said end surfaces of said lasing medium comprises transmitting a plurality of sources of said pumping radiation toward both of said end surfaces of said lasing medium.

12. The method set forth in claim 1, wherein said laser system comprises a laser source.

13. The method set forth in claim 1, wherein said laser system comprises a laser amplifier.

14. Apparatus for end-pumping a laser system having a lasing medium with two generally opposed end surfaces and a generally circumferential side surface, comprising:

means for transmitting pumping radiation toward at least one of said end surfaces of said lasing medium; and

means for directing said transmitted pumping radiation to reflect from said side surface of said lasing medium as is passes through said lasing medium.

15. The apparatus set forth in claim 14, wherein said means for directing directs said transmitted pumping radiation to reflect from said side surface of said lasing medium by substantially total internal reflection.

16. The apparatus set forth in claim 14, further comprising a reflective coating applied to said side surface of said lasing medium and wherein said means for directing directs said transmitted pumping radiation to reflect from said reflective coating.

17. The apparatus set forth in claim 16, wherein said reflective coating applied to said side surface of said lasing medium comprises a specular reflective coating applied to said side surface of said lasing medium.

18. The apparatus set forth in claim 16, wherein said reflective coating applied to said side surface of said lasing medium comprises a diffusive reflective coating applied to said side surface of said lasing medium.

19. The apparatus set forth in claim 14, further comprising:

a diffusive area of said side surface of said lasing medium;

a reflective coating to said diffusive of said side surface of said lasing medium; and

wherein said means for directing directs said transmitted pumping radiation to diffusively reflect from said reflective coating.

20. The apparatus set forth in claim 19, wherein said diffusive area of said side surface of said lasing medium comprises an etched area of said side surface.

21. The apparatus set forth in claim 19, wherein said diffusive area of said side surface of said lasing medium comprises a roughly ground area of said said side surface.

22. The apparatus set forth in claim 14, wherein said means for transmitting said pumping radiation toward at least one of said end surfaces of said lasing medium comprises a single source of said pumping radiation that transmits said pumping radiation toward a single one of said end surfaces of said lasing medium.

23. The apparatus set forth in claim 22, wherein said source of said pumping radiation comprises a laser diode source.

24. The apparatus set forth in claim 14, wherein said means for transmitting said pumping radiation toward at least one of said end surfaces of said lasing medium comprises a plurality of sources of said pumping radiation that transmit said pumping radiation toward a single one of said end surfaces of said lasing medium.

25. The apparatus set forth in claim 24, wherein said plurality of sources of said pumping radiation comprises a plurality of laser diode sources.

26. The apparatus set forth in claim 24, wherein said plurality of sources of said pumping radiation comprises four laser diode sources.

27. The apparatus set forth in claim 14, wherein said means for transmitting said pumping radiation toward at least one of said end surfaces of said lasing medium comprises a plurality of sources of said pumping radiation that transmit said pumping radiation toward both of said end surfaces of said lasing medium.

28. The apparatus set forth in claim 27, wherein said plurality of sources of said pumping radiation comprises a plurality of laser diode sources.

29. The apparatus set forth in claim 27, wherein said plurality of sources of said pumping radiation comprises four laser diode sources.

30. The apparatus set forth in claim 14, wherein said means for directing comprises at least one lens system.

31. The apparatus set forth in claim 14, wherein said means for directing comprises at least one prism system.

32. The apparatus set forth in claim 14, wherein said laser system comprises a laser source.

33. The apparatus set forth in claim 14, wherein said laser system comprises a laser amplifier.

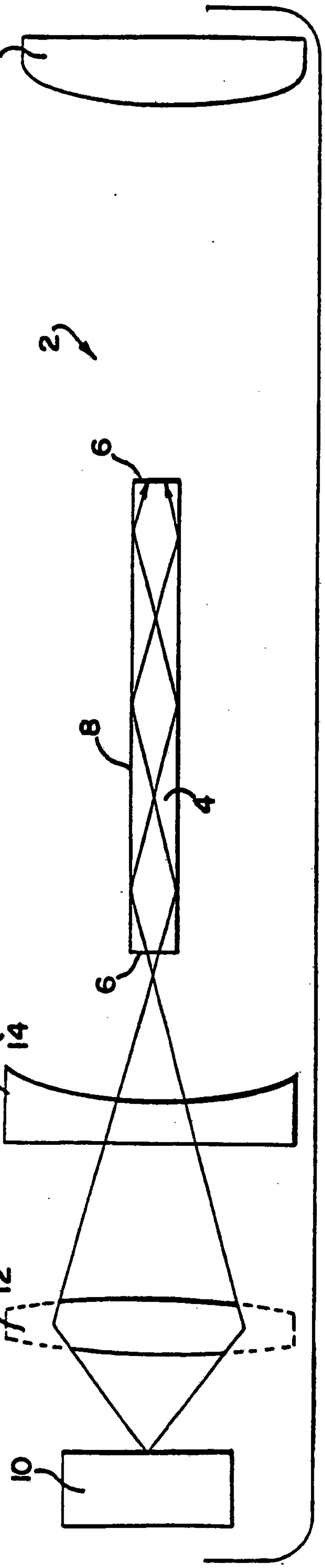

FIG. 1

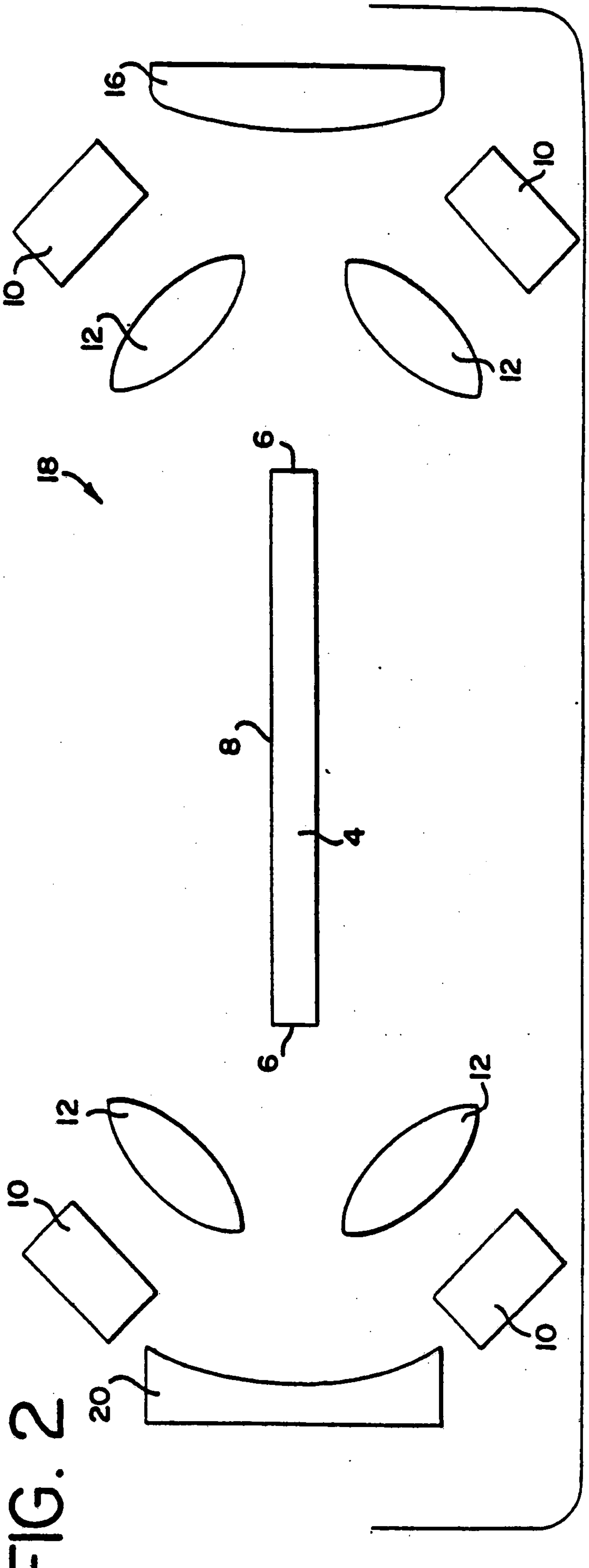

FIG. 2

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 H01S3/094

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H01S

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
X	US,A,3 982 201 (L.J. ROSENKRANTZ ET AL.) 21 September 1976	1,2,9, 10, 12-15, 22-25, 32,33
	see abstract; figure 2 see column 2, line 42 - column 3, line 5 ---	
X	GB,A,2 004 413 (UNITED STATES DEPARTMENT OF ENERGY) 28 March 1979	1,9, 12-14, 22,30, 32,33
A	see page 2, line 30 - line 42; figure 4 ---	3,4,16, 17
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IV. CERTIFICATION

1

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
26 AUGUST 1993	01 SEP 1993
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	BATTIPEDE F.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
X	DE,A,2 844 129 (SIEMENS) 24 April 1980 see abstract; claims 1,4; figure 2 see page 8, line 17 - line 30 ---	1,3,4,9, 11-14, 16,17, 22,27, 32,33
A	FR,A,2 356 296 (INSTITUT FÜR ANGEWANDTE PHYSIK DER UNIVERSITÄT BERN) 20 January 1978 see page 1, line 1 - line 25 -----	5,18

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

US 9304180
SA 73845

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-3982201	21-09-76	None	
GB-A-2004413	28-03-79	DE-A- 2840077	22-03-79
		FR-A- 2403666	13-04-79
		JP-A- 54053995	27-04-79
DE-A-2844129	24-04-80	None	
FR-A-2356296	20-01-78	CH-A- 597701	14-04-78
		DE-A- 2725675	29-12-77
		JP-A- 52156594	27-12-77
		NL-A- 7706405	23-12-77

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